PROGRAMMED PILOTAGE AS A MEANS OF IMPROVING ROTORCRAFT PERFORMANCE IN LEVEL FLIGHT

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THESIS

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by

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ABSTRACT

Considerable effort and money have been expended on research relating to the next generation of STOL/VTOL aircraft. Since the helicopter offers many advantages not attainable in other direct lift aircraft, expansion of its translational speed range represents an excellent means of improving its competitive position.

Airframe drag reduction and engine duct design, while necessary to the improvement of performance, cannot alone offset the aerodynamic limitations inherent in rotary wing flight. The latter, which have become predominant with the advent of high output turboshaft engines must then be overcome by other means discussed in this paper. Programmed pilotage techniques which utilize real-time flight data to vary aerodynamic parameters are investigated and incorporated in the preliminary design of a high-speed rotorcraft. The rotor speed and the contribution of lift from a fixed wing are thus optimized throughout the flight envelope, thereby greatly enhancing level flight speed characteristics.

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I. INTRODUCTION

Programmed pilotage is the technique of automatically altering flight parameters during flight to optimize performance. This loose definition fits a full spectrum of systems and devices as diverse as autopilots and fuel controls and includes the ramp intakes and wing-swing program on the F-14 airplane.

Helicopter performance was limited in the past by power plant capability. The hover mode received the lion's share of attention and fuselage and rotor design reflected this attitude. With the advent of the turboshaft engine, power available took a substantial step forward. Unfortunately, the fuselage and rotor design remained essentially unchanged. The results have been far from optimal.

Compounding, i.e., addition of wings and auxiliary thrust devices, when coupled with turboshaft engines and modern fuselage designs, has produced dash speeds of nearly twice those of conventional operational helicopters.

This paper will show how programmed pilotage can be used to further increase the high speed capability of rotorcraft. The parameters of concern are rotor RPM and wing lift.

To ensure the success of any hardware system, it must possess either commercial or military potential. Design considerations have generally precluded mixing of the roles, with the exception of transport

vehicles and limited electronic systems. Outlined below are two sets of problems which could be attacked by a compound rotorcraft such as now envisaged.

A. COMMERCIAL AVIATION

With the increased growth of population centers, traffic congestion has led to increased "center to center" travel times for trips of less than 1,000 miles. For example, the average speed by air between downtown New York and downtown Washington, including baggage claim, taxi rides and holding patterns, is only slightly greater than could be achieved by train or automobile: 70 MPH vice 50 MPH. The same problem holds in travel between London and Paris and many other large population centers. Conventional helicopters have shown their value in some of these areas but, with cruise speeds only about twice that of ground transportation, the expense of operation has precluded profitable passenger operation except in a few places.

With a speed capability in the neighborhood of 300 Kts, the "break even" point would occur with fewer passengers and/or would make longer flights profitable. Such usage would also eliminate a great deal of traffic congestion in the neighborhood of metropolitan airports.

Of concern to passengers and to citizens in the flight path of any aircraft are safety and noise. Both of these factors will be discussed later.

B. MILITARY APPLICATIONS

The mission capabilities of such a machine vary throughout the entire range of present helicopter roles. Some, such as external hoist (crane) operations, mine sweeping and plane guard, would receive no benefit from improved dash speed capability.

At the other end of the spectrum, particularly in a hostile environment, attack, search and rescue (SAR), medical evacuation and missile launching fleet defense missions would reap enormous benefits. While some of these missions overlap with those flown by fixed-wing airplanes, the SAR mission in hostile territory has been relegated to the hover-capable (and up until now, extremely vulnerable) helicopter of conventional design. It is with this fact in mind that an ultra-fast rotorcraft is now conceived as a straightforward design project.

II. DESIGN PROBLEM

The design of a high-speed vehicle capable of adequate hover capability is a classic example of compromise. In general, those characteristics which improve the performance in one mode of flight degrade it in the other.

Attempts to produce high-speed rotorcraft with hover capability have met with varying degrees of success in the past. Below is listed a brief review of each of the approaches attempted and a discussion of the capabilities of each type of machine.

A. TILT WING AND TILT ROTOR

These types have been quite successful but suffer from bulky and complex transition equipment. Wing or rotor tilt failure usually precludes a landing in the conventional manner due to blade clearance. Some work has been done with ducted fans and at present seems to provide some hope.

An interesting pioneer effort was the XVIA 'Pogo Plane' which took off vertically from its own tail. The initial transition from vertical to horizontal flight was not difficult, but the transition back to vertical flight with the wing fully stalled, nose pointed skyward, must have been an unnerving experience. The control problem in this type of vehicle is normally handled by use of multiple rotors which, of course, add drag and require more power.

B. DIRECT JET LIFT

The direct-lift method leaves the top end of the speed regime open but at the expense of hover capability. Two distinct methods of lift production are possible. One utilizes vectored thrust from the vertical flight engines that also produce thrust for flight. This is the approach utilized in the Hawker-Siddeley "Harrier." A second method utilizes two distinct engine systems, one for lift and a second for thrust. The advantage of this type lies in a simpler transition from hover to forward flight. This could lead to a weight penalty in that some engines will normally be producing little or no thrust during part of the flight. However, the thrust vector baffles, servos, and controls which are necessary in the other system are not required in this system.

All jet-lift vehicles so far produced suffer severely from limited hover capability in that noise levels and fuel consumption are both very high. The vertical flight mode can practically be used only for take-off and landing and thus limits the mission capability of such machines. High downwash velocities, high exhaust gas temperatures and a low hover endurance all act to limit the value of this approach in high-speed rescue vehicles.

Control systems must necessarily be duplicated, i.e., there must be one for the hover mode, generally of the vectored thrust type, and a second of the conventional fixed-wing type. Further, failure of an engine in the hover can only lead to disaster unless a sufficient number of engines are provided.

C. THE STOWED ROTOR CONCEPT

Some day the stowed rotor machine may provide the forward flight characteristics of the fixed wing airplane and the vertical flight capability of the helicopter. There is currently much research being conducted in this field but, as yet, it is not an engineering problem. Flutter, divergent flapping of rotor blades during rotor shut-down, duplication of control systems, reliable blade fold sequencing, CG shift and other problems face the development of this machine.

It appears that this will not be a next generation VTOL aircraft, but will undoubtedly play an important role if and when the technical difficulties are overcome.

D. THE COMPOUND HELICOPTER

The compound helicopter is limited in top speed but possesses good hover performance. The usual complexities of conventional helicopters exist but the state of the art has progressed to the point where these problems are minimal and, presupposing sound engineering practices and design, the hardware concerned is straightforward and reliable. Such machines have years of experience and application in their background.

In designing the next generation VTOL aircraft, consideration should be given to the straightforward engineering approach to the problem. By building on past experience and employing a few new concepts, a VTOL aircraft capable of turbo-prop airplane speeds and good hover performance can be built based on current technology.

III. DESIGN APPROACH

Previously, helicopters have been designed to hover and airplanes to fly forward. The results have been helicopters with poor forward flight capabilities. Little effort has been expended on streamlining until fairly recently. Notable exceptions include the Fairey Rotodyne (which flew 200 MPH regularly) and the AH-56 Cheyenne, Lockheed's attack machine.

Incredibly, flush riveting, retractible landing gear, full canopies and faired rotor heads have received almost no attention in the past. Flat plate areas have been reduced by nearly 50% by clean-up programs on the S-67 helicopter over the S-61 which share the same rotor/power train.

While such efforts are admirable, flat plate areas of under 12 sq. ft. are only targeted for helicopters. The Fairey Rotodyne (11.0 sq. ft.) was cleaner than what is presently being approached. The difference lies in the fact that this machine was designed as an airplane which could hover rather than as a helicopter which could fly forward.

In compound helicopters, which keep their fuselages substantially level in forward flight, low flat plate areas are maintained throughout the speed range, unlike the pure or vectored-thrust helicopter which requires its fuselage to be tilted forward progressively with forward speed, thereby converting what is intended to be of streamline shape

into a bluff body. The parasite or body drag of pure helicopters is therefore detrimental to high speed capability.

A. INITIAL DESIGN PARAMETERS

<u>Configuration</u>: Single main rotor. Torque compensation by dual outboard propellers mounted on stub wing tips. Dual turbo-shaft engines.

<u>Maximum overgross</u> weight in hover-out-of-ground-effect, at Sea Level standard conditions: 20,000 lb.

<u>Rotor Diameter</u> 50 ft. based on the following:

a. Shipboard stowage limitations

b. Disk loading of about 10 lb/ft^2

<u>Maximum Forward Speed at Sea Level</u> 280 Kts.

B. FORWARD FLIGHT SPEED LIMITATIONS

Under ideal conditions for peak speed, the blades would be simultaneously reaching shock stall conditions on the advancing blade, tip stall on the retreating blade and maximum power, provided the power required is greater than that required to hover under design conditions.

Figure 1 shows the flight envelope for the aircraft, flight being possible within the large triangular areas bounded by lines of constant tip-speed ratio and constant advancing blade-tip Mach number [Reference (3)].

Steady state flight has been achieved with tip-speed ratios (μ) greater than unity, but the system is extremely susceptible to flutter. Since periodic torsional moments due to center of pressure shift are present, the torsional stiffness would have to be greatly enhanced if μ over 0.9 were utilized.

Advancing blade-tip speeds of the order of Mach 0.98 have been achieved but such speeds are not to be expected under other than ideal conditions. Advancing tip speeds of the order of Mach 0.95 can be expected to produce minimal shock stall, particularly if the blade tips are of reduced thickness and swept as in the UH-1 "Huey-Plus" and S-67 "Black Hawk."

The above speed limitations are based on rotor aerodynamic properties. Given a clean airframe and ample power, a rotor aircraft can fly <u>operationally</u> at 300 MPH.

Essential flight instruments in such an aircraft would include a blade-tip Mach probe on which the pilot could read maximum tip Mach number and a "Mu gage" which would simply compare the aircraft Mach number with the maximum blade tip Mach number. Engine speed can be altered to maintain constant tip speed at higher airspeeds. When the maximum "μ" value is obtained, at maximum tip Mach number, "Red-Line" would be reached for the given density altitude conditions. Computation of rotor tip Mach number based on fuselage Mach number and rotor tachometer output could similarly be used as the governing signal.

Flight data might enlarge the envelope and increase the top speed if the tip-speed ratio could be increased without undue stress on the airframe and rotor system.

C. TORQUE COMPENSATION

The torque supplied to the rotor system by the engines, through the transmission, in powered flight must be balanced by an equal and opposite torque applied by some other device. Several methods have been employed in the past, including:

1. A second counter-rotating rotor, mounted above, beside or behind and either intermeshing with or clearing completely the first rotor.

2. Adoption of a thrust device with axis perpendicular to that of the main rotor and offset by some distance. The tail rotor and offset thrust rotor are examples of this type.

The torque problem can likewise be avoided by use of a self-propelled rotor utilizing pressure jets or ramjet engines mounted at the tips. Both of these methods eliminate all torque except that owing to the friction of the rotor shaft, which is very small. Further, the transmission system can then be eliminated, cutting cost, weight and complexity. The disadvantage of such systems includes high fuel consumption rates and high noise levels while the rotor is loaded.

The Fairey Rotodyne, a relatively sophisticated compound rotorcraft, utilized a pressure jet rotor of 90 ft. diameter. The aircraft

performed very well and held the world's rotorcraft speed record at something over 200 MPH in 1957. The noise problem, however, forced the end of development on the aircraft. At a gross weight of 60,000 lb., the disk loading of the Rotodyne was 9.4 lb/sq. ft., or slightly less than that of the machine proposed here, indicating that the pressure jet or the less efficient and noisier ram jet system would be unacceptable in the proposed aircraft.

The alternatives remaining open include only those applicable to a single-rotor design. The high-speed capability of any aircraft is seriously hampered by the addition of a rotor. Multiple rotor designs are less efficient at high speeds than single rotors, owing to their drag. A possible exception is Sikorsky Aircraft's proposed Advancing Blade Concept (ABC) which utilizes a coaxial rotor arrangement of very stiff, small-diameter rotors operating at very high tip-speed ratios. This approach, while interesting and perhaps promising, remains to be proven in flight.

The tail rotor is a proven method of providing both yaw control and torque compensation throughout the flight regime of the single-rotor helicopter. Pioneered and perfected by Sikorsky, it is a reliable system capable of producing high torque values with relatively little power drawn away from the main rotor owing to its large moment arm. With a stable fuselage, however, aerodynamic stiffness of the aircraft in yaw can balance rotor torque. Thus, in a properly designed compound machine at high speed, the wings unload the rotor, reduce the rotor

torque (and hence the required counter-torque) and the tail rotor becomes an aerodynamically inefficient rudder which degrades performance.

Ducted tail rotors and variable vanes in propeller slip-streams have met with limited success. Piasecki Aircraft has attempted the latter vectored-thrust method in a research aircraft. The obvious advantage of this system is that the vectored thrust can overcome torque in low-speed flight and drag in high-speed flight. This leads to the offset thrust rotor system adopted for use in the present design study.

IV. DESIGN PARAMETERS

A. ROTOR SPEED GOVERNING SYSTEM

In order to provide optimum forward flight speed potential, maximum values of blade tip Mach number and tip speed ratio must be achieved simultaneously. This point is the apex of the curve shown in Figure 1.

Maximum blade tip Mach number is taken to be a high subsonic value based on current technology as mentioned in the rotor system section of this paper. Supersonic tips are possible only at the expense of greatly increased power requirements and noise levels.

Since the airspeed of the advancing blade increases with forward aircraft airspeed, critical blade tip Mach number may be experienced at relatively low forward airspeed. Indeed, the blade tips could reach this condition in a hover, if the rotor angular speed were high enough.

Throughout the years, several proposals have been made to help eliminate or alleviate this problem. The multi-speed transmission has been advanced as one solution, using high rotor speed in the hover and low rotor speed in forward flight. The disadvantages of this approach lie in mechanical complexities and finite gear ratios or steps in rotor speed.

Control of rotor speed by use of engine governing has previously met with limited success owing to overloading of bearings and the

inability of engines to perform satisfactorily over a wide RPM range. Reciprocating engines fitted with superchargers simply cannot produce sufficient manifold pressure at low speeds to provide peak horsepower output.

Gas turbine engines can operate over wide speed ranges, i.e., with speed fluctuations of the order of 20% provided the bearings are designed for this type of engine operation. Of course, some performance will be lost by this compromise, but the result is an effectively infinite gear ratio within the selected engine speed range.

By the use of a free power turbine connected to the main transmission, the rotor speed can be monitored and used as a fuel control input. Additional inputs include the outside air temperature and a selected rotor speed.

The system mentioned above is the one used in many modern gas turbine helicopters. The selected rotor speed is governed by an electrical or mechanical signal pre-set by the pilot in the cockpit and is the rotor speed which the fuel control will attempt to maintain, varying only by the mechanical and hydraulic lag in the system.

The rotor tip speed signal replaces the pilot input in this system, adding one more loop in the control network. The tip-speed sensor is a simple Mach probe which measures the sinusoidal variation in tip Mach number. The peak value of this signal is compared to the maximum permissible advancing tip Mach number. The resultant error signal provides the selected rotor speed input signal. Governing would

not commence until the advancing tip speed reached its predetermined maximum value.

The result of this hardware is a constant Mach number at the advancing blade tip, reducing compressibility effects at higher airspeeds.

The second boundary of the aircraft speed performance envelope is formed by the constant tip-speed ratio line. A tip-speed ratio gage could very simply be produced by mounting a simple Mach probe on the aircraft and by comparing tip Mach number to fuselage Mach number, whence a direct readout would be achieved. To achieve maximum airspeed for any altitude and/or temperature condition, the pilot need merely accelerate the aircraft (flying along the constant tip-speed Mach number line) until the limiting tip speed ratio (μ) is achieved.

Hover rotor speed is based upon 125% of minimum (cruise) rotor RPM based on rotor RPM instead of being directly read in tip Mach number. This is taken to be the 100% rotor RPM point and corresponds to 288 RPM for the 50 ft. diameter rotor.

B. TORQUE COMPENSATION AND THRUSTER SYSTEM

The offset thrust rotor system is merely a variation of the tail-rotor system. In this aircraft, two propellers (rotors) are mounted on the wings near the tips. The power requirements for the two propellers will be greater than for a single tail rotor because they are offset by only the wing semi-span. There will be plenty of power available, however, as top speed will require more power than hovering flight under normal circumstances.

While hovering, with rotors turning counter-clockwise, the fuselage would tend to yaw nose right. This means that an increase in collective pitch of the starboard propeller and simultaneous decrease in collective pitch of the port propeller must be applied to balance the rotor torque. The system could be made more efficient if the port propeller were allowed to produce negative (reverse) thrust by going to negative pitch. Differential collective pitch is provided through normal rudder pedals.

An additional cockpit control is required for thrust variation to change simultaneously the pitch on both propellers. A collective twist trip or electric trim switch is used. This is equivalent to the throttle in a reciprocating-engined helicopter. The Lockheed-California Company calls the pitch change control of thrust on the AH-56 the "Beta Control."

The propellers are driven by the engines through the main transmission and shafting, in much the same way as a tail rotor system is powered. This allows for aircraft controllability in the event of an engine failure or changeover to autorotation. In the event of dual engine failure at high forward airspeed (high propeller blade angle), the collective pitch lever would be moved to the lowest pitch position (it will already be very close to it) and the twist grip moved to its closed position. The propeller blades will be at low or negative pitch (producing reduced drag or even negative windmilling). Lockheed's AH-56A "Cheyenne" utilizes a "Beta dump" system which drives the pusher propeller into a negative pitch condition (windmill brake state) upon loss of engine power so that the main rotor receives energy from

the airstream, a steady state autorotational rotor speed being thereby more quickly achieved.

The normal transition from the hover to high-speed flight should be smooth and rapid. Initially, the propellers are producing high thrust in opposite directions. The transition is commenced by tilting the tip path plane forward as in a conventional helicopter. As translational speed increases, the power required (and counter-torque required) decreases. Collective rotor pitch is reduced and pitch is increased on both propellers simultaneously (i. e., the left propeller produces less negative thrust, the right more positive). The heading can still be controlled from foot pedals by differential pitch change. Further increase in forward speed produces sufficient lift from the fixed wing to allow a further reduction in the collective pitch. This allows more engine power to be available for use in providing forward thrust. Torque compensation and heading control are still available since counter-torque is a function of the difference in thrust produced by the propellers.

A detent should be provided for the collective pitch lever at the predetermined rotor loading (20% of maximum gross weight) so that, once the high-speed regime is reached, the pilot need not again concern himself with the collective pitch lever. The pilot should, however, be able to over-ride the detent in the event of change-over to autorotation. A simple spring device would suffice.

As airspeed increases into the rotor tip speed governing range, the engine speed, and hence the propeller speed, will decrease. In

order to maintain thrust, the pilot would be required to increase the collective pitch of both propellers simultaneously. The thrust and engine power output are controlled by the twist grip, making it completely analogous to the throttle in reciprocating engined machines. Attitude is controlled by the cyclic pitch control and heading by foot pedals.

The propellers are simpler than tail rotors in current use since they will be subjected to essentially axial flow, thus eliminating the need for flapping hinges. This means that simple and reliable constant speed propellers with hydro-mechanical control can be used for thrust and/or torque compensation.

The simultaneous pitch change signals from the twist grip and the differential signals from the foot pedals must be mixed.

One mechanical mixing method is to provide a sliding-rotating beam. The slide provided simultaneous propeller pitch change ("Beta" Control) and the beam rotation provides differential propeller pitch change. The outputs are fed into the hydro-mechanical propellers. Mechanical mixing has the advantage of being independent of hydraulic and electrical systems.

Some typical values of propeller thrust requirements are seen in the Figure 3 of this paper.

C. THE FIXED WING SYSTEM

The fixed wings serve four important functions:

1. Provide propeller offset to produce yawing moments necessary to unbalance rotor torque and thereby control the aircraft heading throughout the flight envelope.

2. Produce lift during forward flight as the main rotor becomes off-loaded thus preventing the onset of retreating blade tip stall with increasing forward airspeed.

3. Enhance maneuverability by increasing "g" loading capacity.

4. Provide for weapons and fuel stations in special missions such as ferry flights.

The initial transition of rotor off-loading should be completed by some speed below the aircraft red-line in order to simplify the pilot's task. Upon completion of the transition, the collective pitch control will be in the detent and need not be used again until the aircraft is slowed below full-transition airspeed, for that particular gross weight.

The pilotage simplification in the high speed regime and the requirement to maintain the tip-path plane and fuselage essentially level at high speed, owing to drag considerations, lead to some mechanical complications.

The wing lift must remain constant with increasing velocity, once the rotor off-loading has been completed, for level flight acceleration. Conventional fixed wing airplanes accomplish this by reduction of fuselage angle of attack resulting from use of elevator control. This would not be a satisfactory method in this aircraft since the tip-path plane is to remain essentially level.

The basic wing parameters, unlike those for fixed wing airplanes, are based upon minimum weight and maximum speed considerations. Variable high left devices should be capable of increasing the total

wing lift to the maximum weight condition at the transition completion speed. This means that some high lift device will be employed at all times during the flight with the exception of the special case of minimum weight at maximum speed.

With increasing dynamic pressure, the effect of the high lift devices are reduced in such a manner that the wing lift remains constant while attitude remains fixed.

D. FIXED WING LIFT CONTROL SYSTEM

The product of wing area and lift coefficient is a measure of the "effectiveness" of the HLD (high lift devices) employed. The HLD effectiveness must follow the curve shown in Figure 2, corresponding to the gross weight of the aircraft at any particular instant.

By employing a cam with two degrees of freedom, the high lift device effectiveness can be correctly varied with dynamic pressure change for any gross weight. Dynamic pressure variation can be easily transformed into linear motion of the cam by use of a plate upon which ram air impinges. Linear motion of the cam can be resisted by a spring. One configuration is shown in Figure 4.

Rotation of the cam about its longitudinal axis corresponds to selection of the proper gross weight curve in Figure 2. This cam surface selection is made by the pilot based upon altitude retention. If the aircraft were to climb while accelerating, the wing would be producing too much lift for the aircraft's gross weight. The pilot,

using an electric "trim" switch, would rotate the cam to select a lower gross weight curve on the cam. Similar pilot reaction would be required with a decrease in fuel weight. Conversely, the cam would be rotated in the opposite direction by the pilot if the aircraft were to lose altitude during acceleration.

A barometric altitude hold system would be useful in positioning the cam in the rotational sense for acceleration in level flight and in maintaining pressure altitude as fuel is burned.

If the HLD effectiveness and position were not linearly related, the cam could be cut to follow the HLD position directly with change in the dynamic pressure for any gross weight. HLD effectiveness is a linear function of the incidence angle of a tilt wing, for constant fuselage angle of attack.

The cam follower provides an input signal into the HLD actuator valve. The system described is applicable to the tilt wing or the variable HLD method of lift control retention.

E. VARIABLE HIGH LIFT DEVICES

High lift devices which change both airfoil shape and size are presently in use. Owing to the fact that they would be in operation throughout the flight, the high lift devices must be reliable. Hydraulically operated leading and trailing edge flaps lend themselves ideally to the above application, the Fowler type being particularly attractive since drag is a function of wing area. High speed wing drag is thereby reduced from what it would be using a simple flap.

The devices mentioned above are somewhat complex but are currently in use. Failure of any portion of the system, while a possible cause for mission abort, would not be catastrophic.

F. THE TILT WING METHOD

Another means of controlling lift would consist of varying wing incidence angle while maintaining a flat fuselage attitude. This method has the advantage that a single device is required, i.e., a wing tilt mechanism. The total travel required is under 12° and can be controlled by a method identical to the one discussed above. The disadvantage of this system is that a more powerful hydraulic system would be required to tilt the wings than to operate the high lift devices, particularly if external stores were mounted on the wings. The wings can be made to pivot while the tip mounted gear boxes and propellers remain fixed with reference to the fuselage.

Computations based upon such a device are included in this paper. Note that extreme nose low attitudes should be avoided to preclude negative wing lift.

G. BASIC WING--REQUIREMENTS

The wing should have as large a span as possible from the standpoint of torque compensation and induced losses. Low propeller thrust would produce large control moments, and hence increase hover capability. Unfortunately, bending moments likewise increase as the span is made larger. This is of concern as substantially total aircraft thrust is produced at the wing tips.

A second limitation is one of storage space. Allowance should be made for the propeller arc radius on each wing. For this reason the total span is limited to 30 feet.

The wings should be foldable for shipboard stowage. Owing to their small size, a manual folding system is considered adequate.

V. TRANSITIONAL FLIGHT

The transition from zero altitude and zero velocity to cruise altitude and cruise air speed can be thought of as being effected by three distinct steps or bands. While in actual practise the transition will be smooth, simple and safe, it is described here as comprising distinct maneuvers.

A. THE VERTICAL TAKE-OFF AND HOVER

This is accomplished as in the conventional turbine-powered helicopter, i. e., ending in a low hover in ground effect. Heading is controlled by foot pedal displacement (differential thrust control), roll and pitch by cyclic pitch control and altitude by collective pitch control. An interesting feature of compound helicopters is their ability to vary fuselage attitude in pitch while hovering over a spot. This is achieved by balancing the propulsive component of an inclined lift vector with propeller thrust. Military applications include increased field of fire and increased visibility in hovering flight.

B. HOVER-DEPARTURE TO TRANSITION-COMPLETION AIRSPEED

The hover departure could be accomplished by two distinct methods. The difference lies in the source of the thrust force used to accelerate the aircraft. In a conventional helicopter the lift vector is tilted forward by use of cyclic pitch change. Collective pitch is increased momentarily and the aircraft accelerates.

The hover departure of a conventional helicopter has the advantage that it is a maneuver understood and practised by helicopter pilots and requires no additional training.

The compound helicopter can achieve a horizontal thrust vector while maintaining a flat fuselage attitude. The pilot merely maintains the fuselage attitude and increases total propeller thrust. This transition requires some pilot training, but has the advantage of simplicity. The attitude change associated with a conventional departure is avoided, a real advantage in foul weather or in the event of engine failure where the aircraft is committed to re-land.

Throughout either type of hover departure, the pilot is required to control the aircraft heading with "rudder" and to control the rotor thrust with the collective pitch lever.

Owing to the shape of the power required curve, the rotor torque decreases with increase in velocity throughout this region. The fuselage tail-fin combination increases the weathercock stability with velocity. The resultant required moment of the anti-torque system decreases with increase in velocity. This moment is produced by the difference in propeller thrusts while the sum of propeller thrusts is used to overcome drag. This means that both propellers are producing thrust to overcome drag while the necessary moment is being produced. Herein lies a major advantage of the offset propeller anti-torque system.

The wings provide increasing lift throughout the initial phase of the transition, allowing the rotor power to be decreased and the

propellers to be more highly loaded at a lower airspeed than if wings were not provided.

A further increase in air speed requires less collective pitch, as the wings then carry more of the aircraft's gross weight. When the collective control reaches the spring detent, the "transition completion airspeed" is reached. This speed is dependent upon gross weight and density altitude. The pilot need not concern himself with matching an airspeed and gross weight, but rather only that the aircraft maintains altitude with the collective in the detent.

C. TRANSITION COMPLETION AIRSPEED TO RED LINE AIRSPEED

A still further increase in forward airspeed requires a reduction in the effectiveness of the high lift devices system on the fixed wings. The pilot needs only to "trim out" tendencies to climb or descent with his cyclic stick "trim" switch which rotates the cam to the correct surface so that the total aircraft lift will remain constant with increasing dynamic pressure.

Throughout the entire high-speed phase of flight, it is of supreme importance that the pilot maintain the tip path plane, and hence the fuselage, level with the cyclic stick to minimize drag. There will be an increasing tendency for the nose to pitch up with increasing airspeed. As the pilot strives to maintain a level attitude, forward stick pressure is required during acceleration. For this reason, a stick trim system of the type commonly in use is incorporated.

Further increases in airspeed will eventually lead to compressibility effects on the advancing blade. Once the advancing tip has reached Mach 0.95, the rotor governing system will reduce the rotor rotational speed at a rate such that the advancing tip Mach number remains constant.

The reduced rotor speed results in a lower propeller speed and thrust. The pilot reaction required is to increase pitch on both propellers as their speed decreases.

The maneuver is entirely reversible at any point. The pilot workload is somewhat greater than in a conventional airplane and is perhaps equal to that in a conventional helicopter.

Any malfunctioning of the transition devices would not appear to be catastrophic in nature if all failures of the high lift devices are symmetric. Failure of the rotor speed governing system could result in an excessive rotor speed leading to shock stall of the blade tips, or a low rotor speed leading to control difficulty and possibly precluding hovering flight, in which case a conventional "run-on" landing may be made.

VI. CALCULATIONS

Classical airplane and helicopter performance equations have been used to calculate lift and drag. The sum of wing and rotor lift must necessarily equal the gross weight of the aircraft.

The airfoil selected was an NACA 4424. The lift coefficient was restricted to a value of 1.0 to account for maneuvering flight. The size of the wing was based upon the transition completion airspeed at maximum gross weight, a rotor off-loading of 80% of maximum gross weight and upon the value of the coefficient given above.

The fuselage parasite power was computed based upon an equivalent flat plate area of 10.0 sq. ft. This drag comprised the major component of the total drag power.

For the known wing lift, the rotor lift as well as the induced and profile powers of the wing and rotor systems were calculated. A constant drag coefficient was assumed for the wing at a mean value of 0.012.

Rotor profile drag computations were made based upon the H-force equations. The propeller drag power was calculated by integrating the elemental propeller drag power over the blade span and multiplying by the number of blades. The velocity used in these calculations was the vector sum of the translational speed of the aircraft and the rotational speed of the propellers.

Hovering flight computations were made based upon equations in Reference 2 plus an elemental drag power analysis and integration over the disk both for the propellers and the rotors. Correction factors were calculated as outlined in Reference 2.

Forward airspeed computations were performed on the IBM 360/67 digital computer. Hover computations were done by hand with the aid of an electronic calculator. Curves of power required are shown in Figures 5 and 6.

Power available computations were made from the information in Reference 3. The engine data were scaled in such a manner that the power required, at maximum speed for sea level and 80% power turbine RPM, was produced by the engines. Transmission losses and accessory requirements were assumed to use 25% of the engine output power.

Curves of power available as a function of airspeed for various output shaft speeds at maximum continuous power settings were plotted from data in Reference 3. A plot of rotor RPM against true airspeed was constructed. From these two curves, a power available plot against true airspeed was derived. The maximum speed performance at altitude could not be readily estimated as decreased RPM test data at high altitude for turbo shaft engines was not readily available. Maximum range and endurance information was, however, available since the engine (and rotor) operated at 100% RPM in the lower speed ranges.

Maximum airspeed was limited by either minimum rotor speed (80% NR) or maximum tip-speed ratio (μ =0.9). A result of interest is that these two limits were achieved nearly simultaneously. When hover data were plotted on the same coordinates, the intersection yielded the maximum out-of-ground effect altitudes for hovering at various gross weights as limited by aerodynamic considerations. (Figure 7)

VII. CONCLUSIONS

Even the most modern of today's helicopters are severly limited in forward flight capability. The key to future developments in helicopter design are closely tied to the variation of certain aerodynamic parameters in flight in order to optimize performance.

It has become apparent that speeds in excess of 300 knots, while possible, are not practical for rotorcraft, at least not at present. Degradation of high speed performance inherent with improved hover performance can be offset to a large extent by programmed pilotage.

Proper application of existing technology could yield a helicopter capable of high sustained speeds and good hover performance. Such a machine offers a low risk option in the search for the next generation of VTOL aircraft.

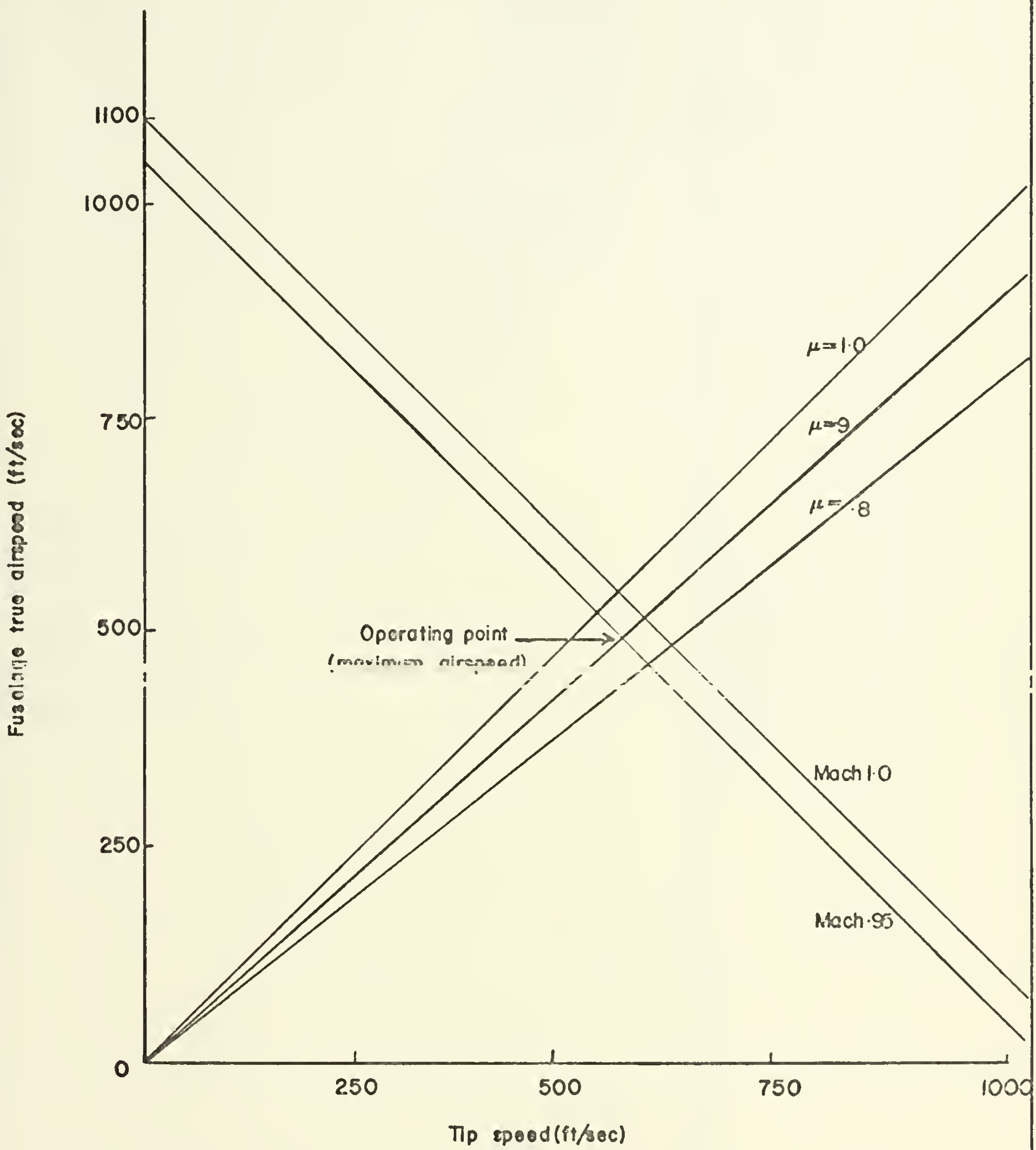


Fig. 1. Graphical Determination of Optimum Speed

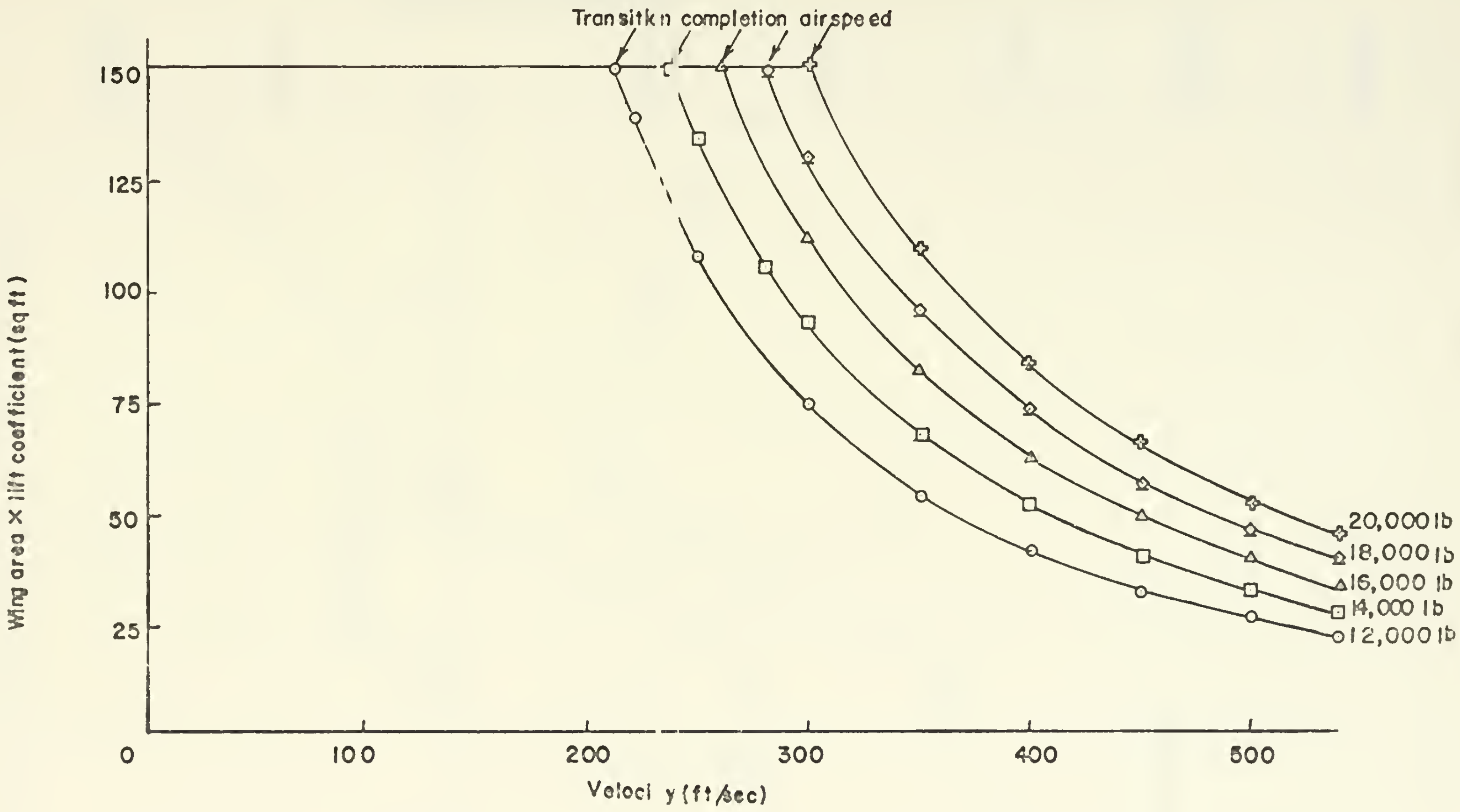


Fig. 2. Sea Level Fixed Wing Lift Requirements

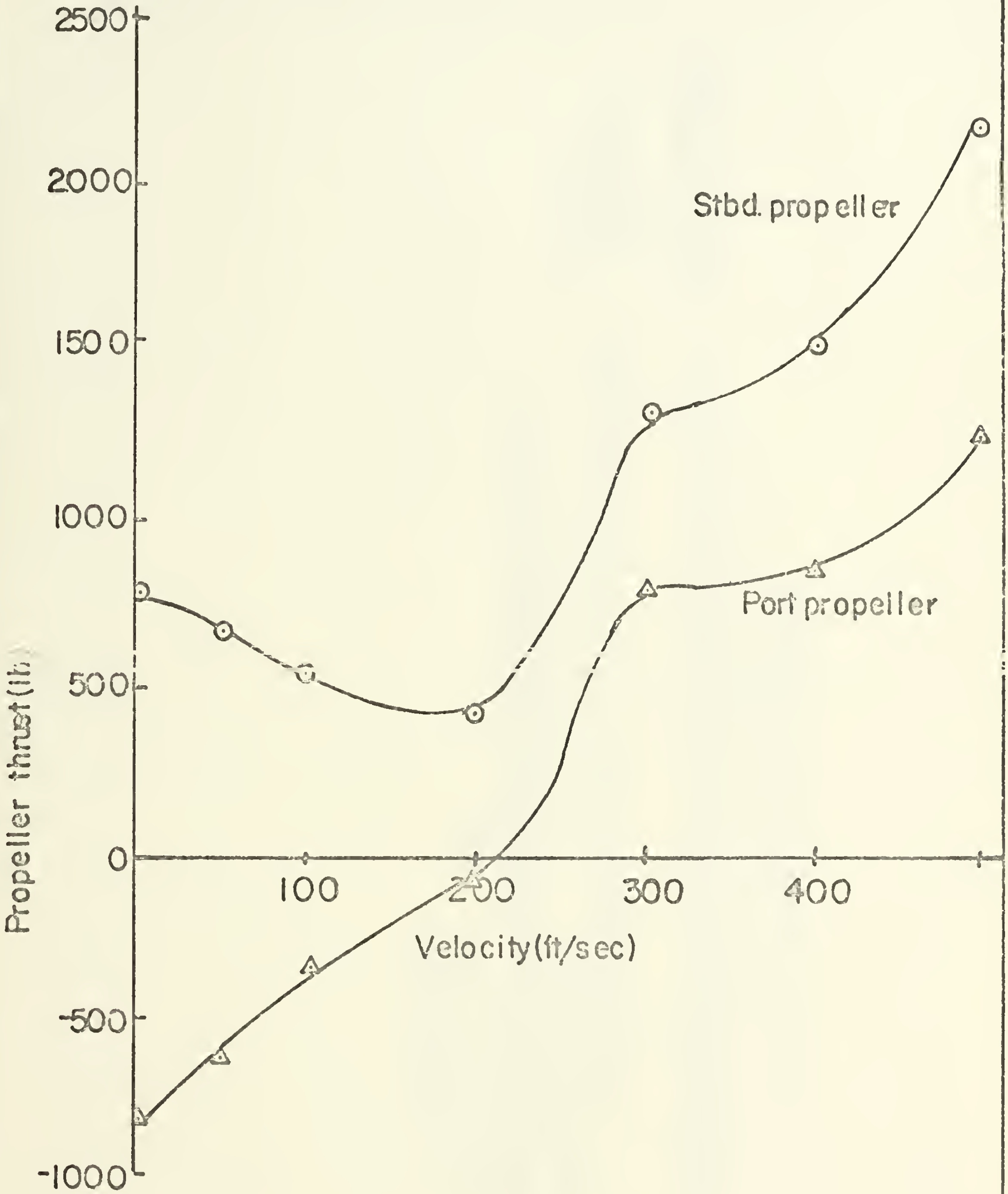


Fig. 3. Propeller Thrust Requirements at 20,000 lb. at Standard Sea Level Conditions

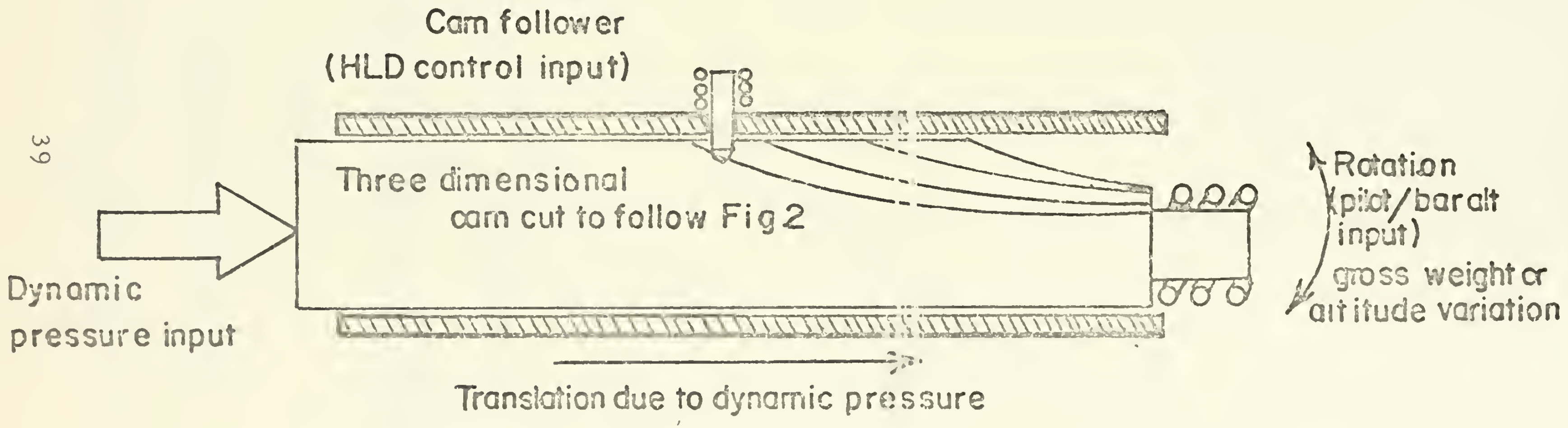


Fig. 4. Mechanical Analog for High Lift Device Control

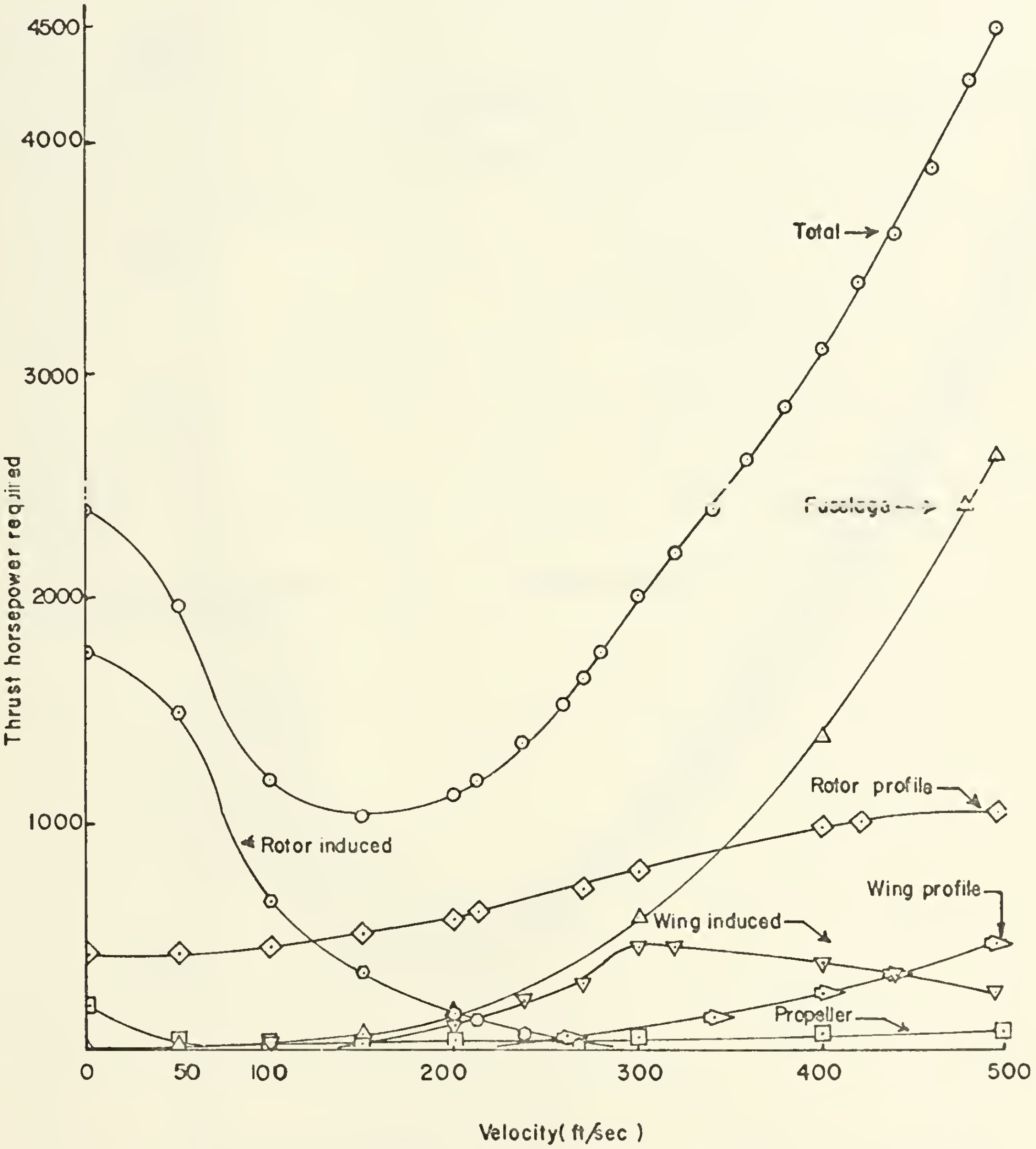


Fig. 5. Drag Power Components

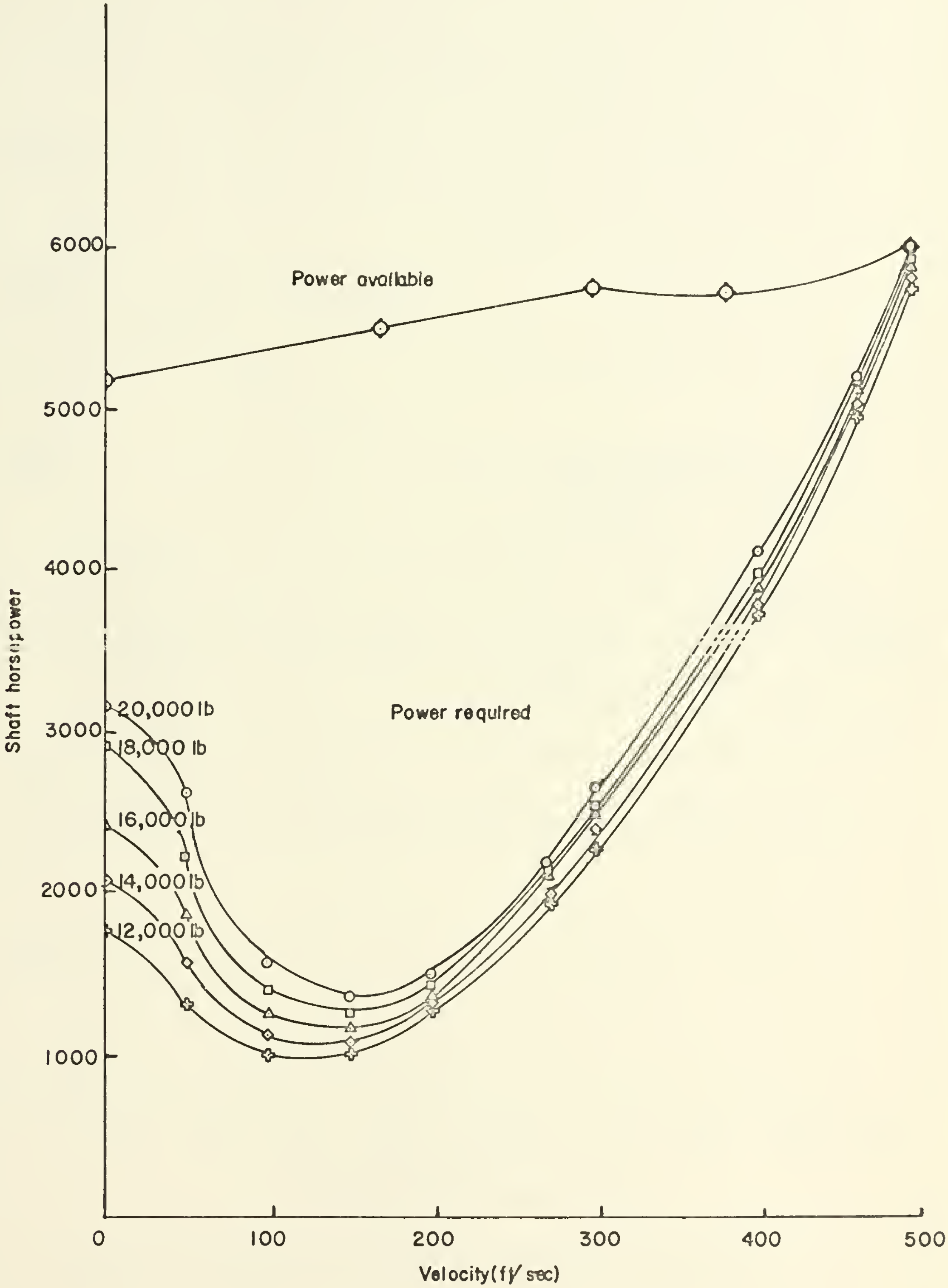


Fig. 6. Sea Level Power Required and Available

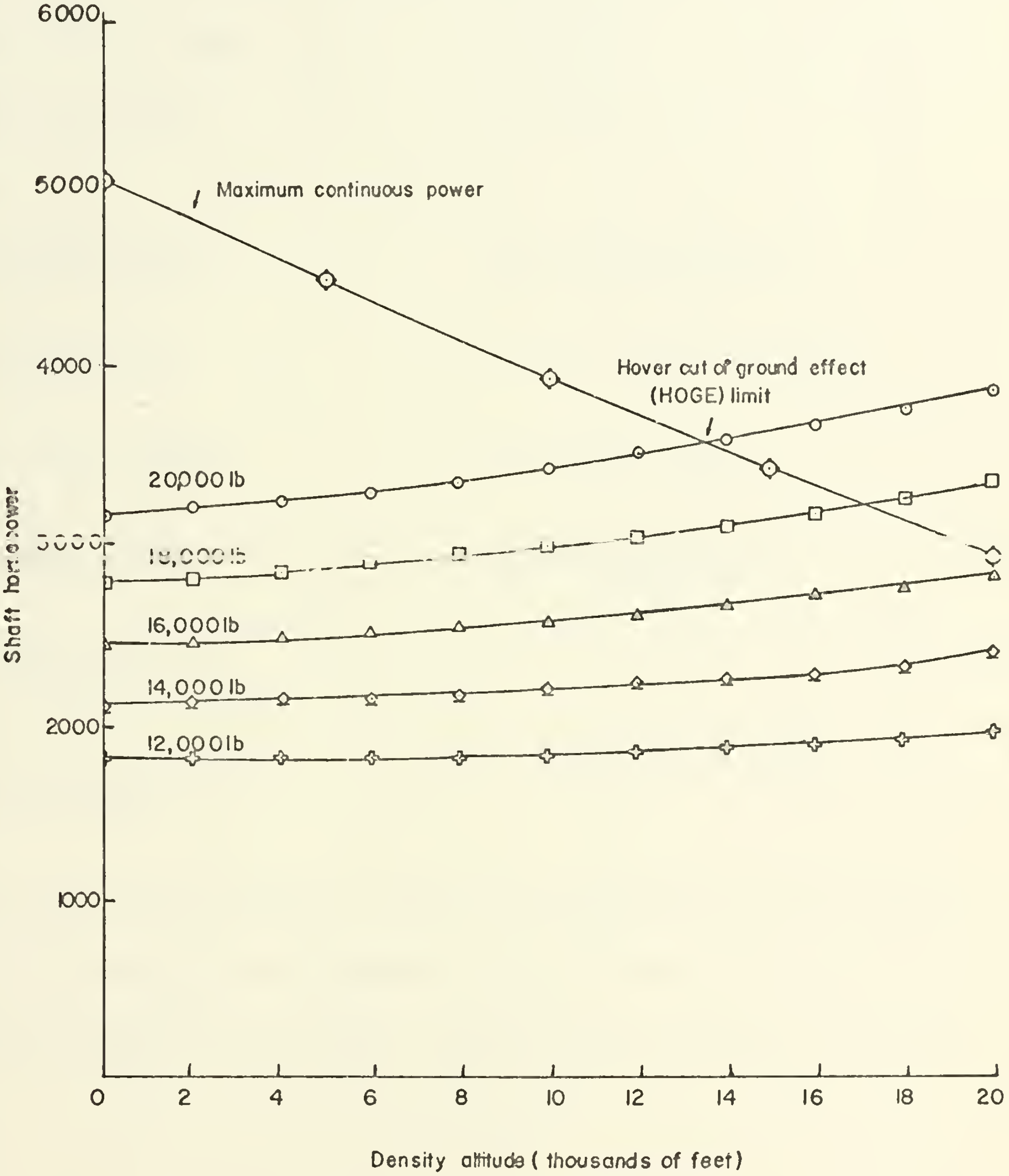


Fig. 7. Hover-Out-Of-Ground-Effect Performance

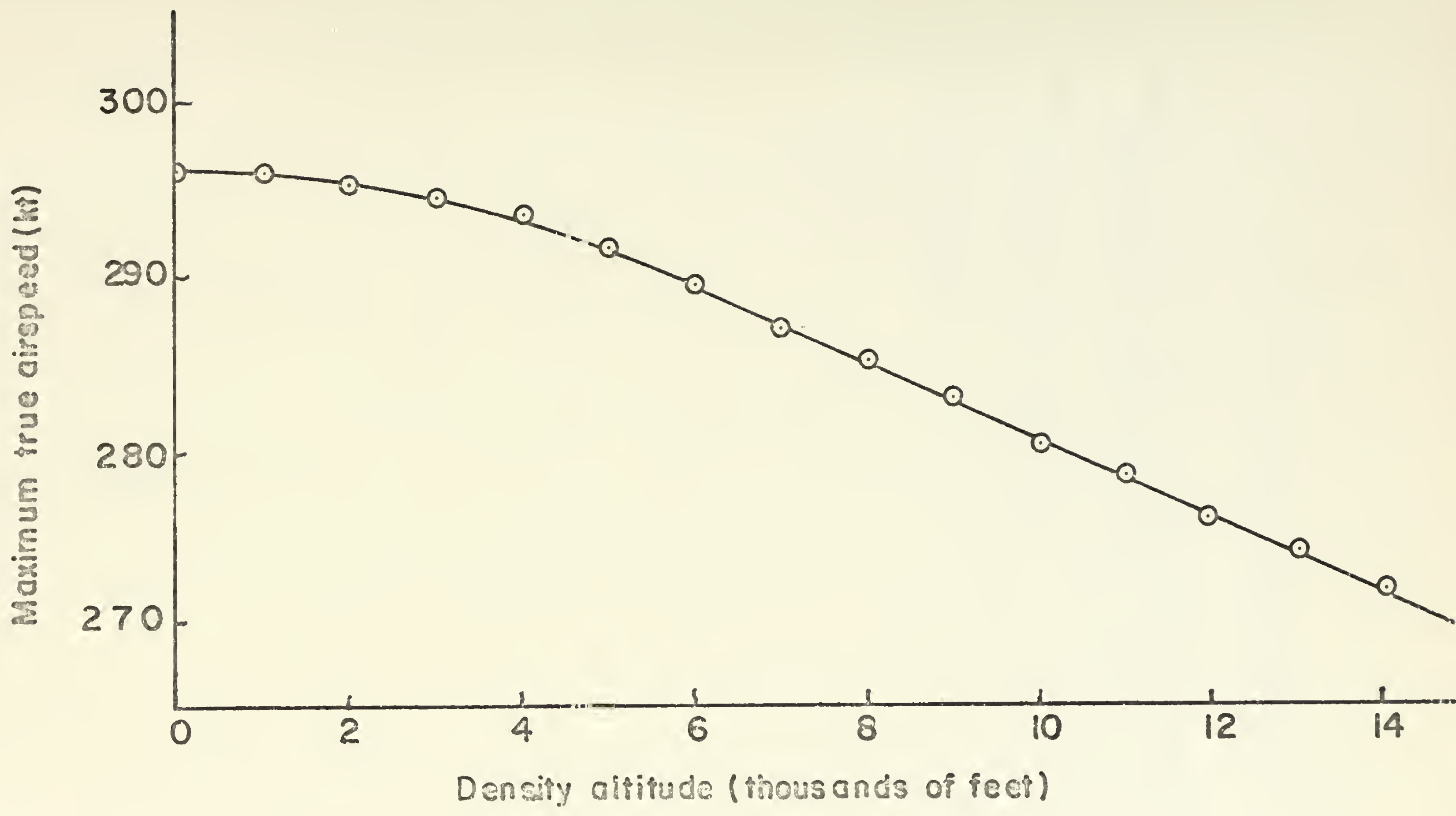
APPENDIX A

COMPUTED PERFORMANCE

Initial Gross Weight	20,000 lb.
Initial Fuel Load	8,000 lb.
Crew	3
Max Ferry Range (SFC=0.70)	1500 statute miles at 130 kts TAS (initial)
Max Endurance (SFC=0.70)	16 hrs at 60 kts (initial)
Max Range (DASH) (SFC=0.70)	820 statute miles
Max Dash Speed	296 kts TAS at SL
Max Hover out of Ground Effect alt. at Max gross weight	13,500 ft DA
Max Rate of Climb at Sea Level	5,700 ft/min (initial)

Optimum Mission Profile: Launch, fly 260 nautical miles at 280 kts to rescue area, hover 15 minutes, recover four survivors and return to base with 10% fuel reserve. Mission elapsed time 2-1/4 hours.

Appendix A. Variation of Maximum Tip Speed Ratio with Density Altitude



Appendix A. Optimum Speed Performance at Altitude

LIFT OF REFERENCES

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2. Gessow and Meyers, Aerodynamics of the Helicopter, Ungar Publishing Company, New York, 1952.

3. Engine Test Report, Allison Model 250-C-18 Turbo Shaft Engine, 1 April 1966.

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13. ABSTRACT

Considerable effort and money have been expended on research relating to the next generation of STOL/VTOL aircraft. Since the helicopter offers many advantages not attainable in other direct lift aircraft, expansion of its translational speed range represents an excellent means of improving its competitive position.

Airframe drag reduction and engine duct design, while necessary to the improvement of performance, cannot alone offset the aerodynamic limitations inherent in rotary wing flight. The latter, which have become predominant with the advent of high output turboshaft engines must then be overcome by other means discussed in this paper. Programmed pilotage techniques which utilize real-time flight data to vary aerodynamic parameters are investigated and incorporated in the preliminary design of a high-speed rotorcraft. The rotor speed and the contribution of lift from a fixed wing are thus optimized throughout the flight envelope, thereby greatly enhancing level flight speed characteristics.

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